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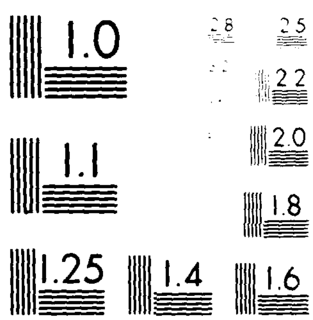
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Our research effort at UCSD has been to develop hybrid optical electronic processing systems capable of high speed computing. We have identified several approaches to hybrid processing worthy of intensive study: (1) optical analog/electronic digital hybrids, employing either a coherent optical processor or a confocal opitica feedback system, and (2) optical digital (nonlinear) /electronic digital hybrids, employing either optical parallel logic or integrated optical logic devices. These approaches are worthy of intensive study because optical

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AFOSR-TR- 82-0488

ANNUAL REPORT

Optical Analog and Hybrid Computer Solution of Partial Differential Equations

Submitted to

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by

Sing H. Lee

Department of Electrical Engineering & Computer Sciences

University of California, San Diego

La Jolla, California 92093

April 1982

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Our research effort at UCSD has been to develop hybrid optical electronic processing systems capable of high speed computing. We have identified several approaches to hybrid processing worthy of intensive study: (1) optical analog/electronic digital hybrids, employing either a coherent optical processor or a confocal optical feedback system, and (2) optical digital (nonlinear)/electronic digital hybrids, employing either optical parallel logic or integrated optical logic devices. These approaches are worthy of intensive study because optical computation offers the unmatched capabilities of parallelism while electronic computation is currently more flexible. Our focus, then, is to combine the powerful features of both optical and electronic computation.

The status of various aspects of our research is as follows:

(1) Optical implementation of statistical pattern recognition. We have begun applying sophisticated digital signal processing theory for statistical pattern recognition to our optical processing system. For example, in the digital processing world, the modified Fukunaga-Koontz transform and the least-squares linear mapping techniques have been proven to be more useful than matched filtering for separating statistical patterns of two and multiple classes, respectively. The cosine transform has also been shown to be valuable in image coding and compression. With the help of computer-generated spatial filters and the coded phase optical processor, which we have developed, we have recently demonstrated the new transforms optically with the significant computational speed benefit inherent to optical parallel processing [1-3]. For example, if the input object contains (1000×1000) pixels and the computer-generated spatial filter contains 128 multiplexed discriminant functions also of (1000×1000) pixels (derived from the training sets of statistical patterns) for one of the new transforms, we obtain the 128 transform coefficients in the output by performing 1.28×10^{14} mathematical operations in parallel.

Our plan of investigation on optical recognition of statistical patterns is to extend from the two- or three-class to multiple-class problems, from black-white single color to multiple color image problems, and from two-dimensional to three-dimensional object problems, etc.

(2) Hybrid system interface. We have recently upgraded our old microcomputer PDP 11/03 to PDP 11/23. The CPU of the PDP 11/23 runs three to five times faster and can accommodate a four times larger memory, although its recent price is about the same as that of the PDP 11/03 six years ago. To accommodate the advanced features of this new microcomputer, we have also modified the laser scanner driver (written in machine language) and the computational algorithms for statistical pattern discriminant functions (written in Fortran).

(3) Hybrid iterative processing. To facilitate hybrid iterative processing we must combine the current capability of computer analyzing optical output with a new capability of computer addressable, coherent optical input. Hence, we designed and constructed a computer controlled CRT with a fiber optic face plate to address a Hughes liquid crystal light valve (Fig. 1). Presently we are evaluating the performance characteristics of this new interface with respect to spatial resolution, spatial distortion (if any), dynamic range (or signal-to-noise ratio), optical coupling efficiency (between the fiber optics plate of CRT to the writing side of the liquid crystal light valve), optical flatness of the read side of the light valve, etc.

We currently plan to apply hybrid iterative processing to study plasma stability or instability, involving the solution of Poisson's equation and the equations of charge motion. Given an initial charge distribution, the optical solution of Poisson's equation will be obtained by the confocal feedback system for potential distribution. From this potential distribution, a microcomputer will calculate the electric field and solve the equations of charge motion, finding

the displacement of the charges during a small time step Δt, and then generate a new charge distribution (Fig. 2). The process continues by (optically) solving Poisson's equation with this new charge distribution, displacing the charges by the electric field according to the equations of motion again and so on, to stimulate the plasma behavior as a function of time. To go through one iteration of computation for a charge distribution in the space of (1000×1000) pixels, it is estimated that our hybrid system will perform more than 100 times faster than a more expensive digital computer (Fig. 3).

Besides applying the hybrid iterative system to study plasma stability, the hybrid iterative system may also be useful to nuclear reactor design, requiring the solution of integral equations for neutron diffusion and transport. These integral equations can be solved optically with speed [4].

(4) <u>Optical design of coherent feedback system</u>. To increase the space bandwidth product of the confocal feedback system, optical design has been performed to determine how (negative-) lens elements can be used to compensate for the aberrations due to the simple (positive-) spherical surfaces of the confocal feedback mirrors. The two optical systems of Fig. 4 have been investigated where the negative lenses have been incorporated into the spherical mirrors of one system and into the liquid gate holders for the spatial filters in the other Details of the investigation are given in Ref. [5], where it is concluded that the mangin mirror system of Fig. 4(a) yields better performance. A set of mangin mirrors has been ordered to experimentally verify the optical design.

(5) <u>Coherent image amplification</u>. The second generation of injection-locked (folded ring) dye laser has been constructed and tested (Fig. 5). An output in excess 10 KW locked to single axial mode HeNe has been obtained. The dye cell for coherent image amplification has also been incorporated into

the confocal processor. The temporal and spectral characteristics of the output from the coherent processor has been studied with a Tropel spectrum analyzer. Figure 6(a) shows one ring in the output from the spectrum analyzer, when the HeNe is operated at single axial mode and the dye cell unpumped. Figure 6(b) shows two rings in the output when the HeNe laser is operated at two adjacent axial modes. Pumping the dye amplifier cell yields the result of Fig. 6(c) which shows the locking of the amplifier cell to a single HeNe mode. Due to the pulsed nature of the pump, the signal is also of a pulse nature, with a frequency spectrum slightly broader than that of a single axial mode He-Ne. But, since the pulse width is about a millisecond, maintenance of the spectral width is very good.

In addition to investigating the use of organic dye for coherent image amplification we began recently studying the uses of BSO crystal and the principles of nonlinear optics (4-wave mixing) also for coherent image amplification. The French group at Thomson-CSF has experimentally observed optical gain [6] and the Cal Tech group has theoretically revealed that an optical gain factor of 20 should be possible [7]. We shall compare the realistic performances of these two methods (dye vs BSO) of achieving coherent image amplification.

We have previously pointed out that optical gain will be valuable to offset loss in the confocal feedback system for more accurate and wider dynamic range optical solutions to partial differential equations, and to demonstrate optical operational amplifiers. Recently, we discovered that optical gain will also help in solving matrix inversion problems for large matrices (Fig. 7). Note that in the optical feedback system in Fig. 7 we have the optical gain element in the forward path and an optical matrix-vector multiplication system in the feedback path.

(6) Digital optical processing. Figure 8 shows the schematic diagram of a digital optical processor (DOP) under development. In the actual optical system which has been constructed, we presently have the optical logic unit (OLU) and a single memory operating (see Fig. 9). The OLU consisting of two optical parallel logic devices (OPAL 1 and OPAL 2) can perform any one of eight possible logic operations on the inputs A and B under microprocessor control. The memory device itself is another OPAL device operated with feedback (β). The intermediate results from OLU can be stored in the memory and later read out for further processing with new inputs.

The microprocessor control for the Digital Optical Processor functions much like the control software of an electronic computer, allowing the user entry of a multiple-line "program" for the DOP, translating this program into a "machine code" (strings of binary digits representing those shutters and logic devices which are to be turned on and off), and, finally, "executing" the program by sequentially directing these "machine code" words to the optical system. Far more capable, then, of simply carrying out a single sequence of logic operations, our optical computer is fully programmable, even boasting its own "high-level" programming language.

We plan next to extend the hardware capabilities of the Digital Optical Processor with the inclusion of additional memories and an x, y image-positioning system (to allow neighbor-cell processing, critical to future algorithm development). The "software" capabilities of our system will also be extended with new algorithms for, among other applications, area-counting and contouring of input images and the solutions of partial differential equations. The light source used in the DOP will be replaced also by an incoherent source.

(7) PLZT devices. We have been studying the fabrication of optical memory and OPAL devices using PLZT of various compositions. PLZT is an attractive

material because it is available in large areas (up to 4" dia.). PLZT devices can be operated up to a microsecond speed (hence faster than the millisecond speed of liquid crystal devices).

In our initial fabrications of PLZT devices, CdS is used as the photodetector because we have much experience with both sputtered and evaporated CdS films. Their characteristics are summarized in Table I. It is interesting to note that the dark resistance of evaporated films supporting current flow on the film plane (i.e. transverse configuration) can be reduced to almost that of sputtered films supporting current flow perpendicular to the film plane (longitudinal configuration). Lower dark resistivities ensure fast device operation.

Our plan for the next two years will be to replace CdS by silicon, on which MOS phototransitors will be fabricated. Later the phototransistors will be combined with another transistor to form optically controllable flip-flops with memory capability as well as high sensitivity. The silicon wafers are to be bonded onto PLZT substrates. Hence, it is hopeful to produce 2-D spatial light modulators and memory devices of large area, speed, sensitivity, and relatively low operating voltage requirements.

(8) Hybrid (IC/IOC) devices and circuits. IOC is known for its high speed capabilities. To take advantage of the speed of IOC logic we study residue arithmetic. The processing algorithm of residue arithmetic offers potential speed advantages because there is no "carry" bit and the computations of all residue moduli can be executed in parallel. Based on unit cells we have also designed modulus IOC logic structures for various computational functions (e.g., addition, subtraction, multiplication and division), for encoding and decoding (see Ref. 8).

In the past few months we made the masks for fabricating unit cells of the hybrid (IC/IOC) circuits shown in Fig. 10. Masks for two kinds of

photodetectors were designed: one is the n^+/p photodiode (Fig. 11a) and the other is $n^+/p/n^+$ photo-effect-transistor (PET, Fig. 11b). These photodetectors are special in that their positive and negative leads are all on the same side of the silicon substrate. Also, the photoactive region of PET can be very small (< 10 μm), which will result in high-frequency and high-gain operations.

Using the masks we have made, we are now fabricating (a) the photo-electronic devices and modulus circuits on a silicon substrate by following the procedures shown in Fig. 12a, (b) the IOC waveguides on a $LiNbO_3$ substrate following the procedures shown in Fig. 12b. The above two substrates will then be bonded together following the procedure in Fig. 12c to form the hybrid (IC/IOC) circuits (Fig. 10c).

Following device fabrication we shall evaluate our system performance with respect to three areas: the photodetectors are to be measured for breakdown voltage, responsivity, dark current, and response time. The electro-optic switch, consisting of the photodetector and IOC waveguide, will be judged for contrast ratio, response time, and cut-off voltage. Finally, the hybrid modulus circuits will be evaluated for power consumption and speed.

Publications since June 1981

1. S. H. Lee, "Optical Recognition of Statistical Patterns." Proceedings of a NASA conference on Optical Information Processing for Aerospace Applications, Hampton, Virginia (Aug. 18, 1981).

2. J. Leger, J. Cederquist and S. H. Lee, "A Microcomputer Based Hybrid Processor at UCSD." Opt. Eng. (May/June, 1982).

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6. J. Cederquist, "Integral Equation Solution Using Coherent Optical Feedback." J. Opt. Soc. Am. 71, 651 (June 1981).

7. S. Johnston and S. H. Lee, "An Improved Optical Design for Confocal Optical Feedback Processing System." To be submitted to Appl. Opt. (1982).

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9. S. Y. Huang and S. H. Lee, "Residue Arithmetic Circuit Design Based on Integrated Optics." SPIE Proceedings Vol. 321 (1982).

Table 1

CHARACTERISTICS OF CdS FILMS

Deposition Technique	Configuration	Dark Resistivity	Dark Resistance[a]	Light/Dark Ratio[b]
Sputtering	Transverse	$5X10^7$ - $5X10^8$	$2X10^{11}$ - $2X10^{12}$	100
Sputtering	Longitudinal	$5X10^7$ - $5X10^8$	$1X10^7$ - $1X10^8$	100
Evaporation	Transverse	$1X10^4$ - $1X10^7$ [c]	$2X10^8$ - $2X10^{11}$	5 - 100

Notes: a) layer thickness 1.5μm -sputtered
.2μm -evaporated
b) Tungsten illumination 1.7mw/cm^2 sputtered
5.4mw/cm^2 evaporated
c) Occured in thin samples

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1. S. H. Lee, "Optical Recognition of Statistical Patterns." Proceedings of a NASA conference on Optical Information Processing for Aerospace Applications, Hampton, Virginia (Aug. 18, 1981).

2. Z. H. Gu, J. R. Leger and S. H. Lee, "Optical Implementation of the Least Squares Linear Mapping Techniques." To appear in J. Opt. Soc. Am. (May, 1982).

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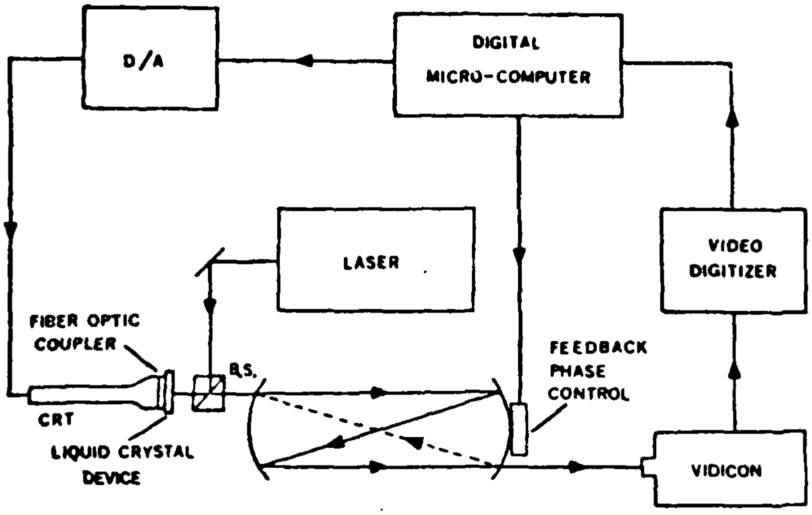


Figure 1a. Schematic diagram showing the microcomputer-controlled video system for real-time image input to coherent optical processor and for real-time analysis of optical output.

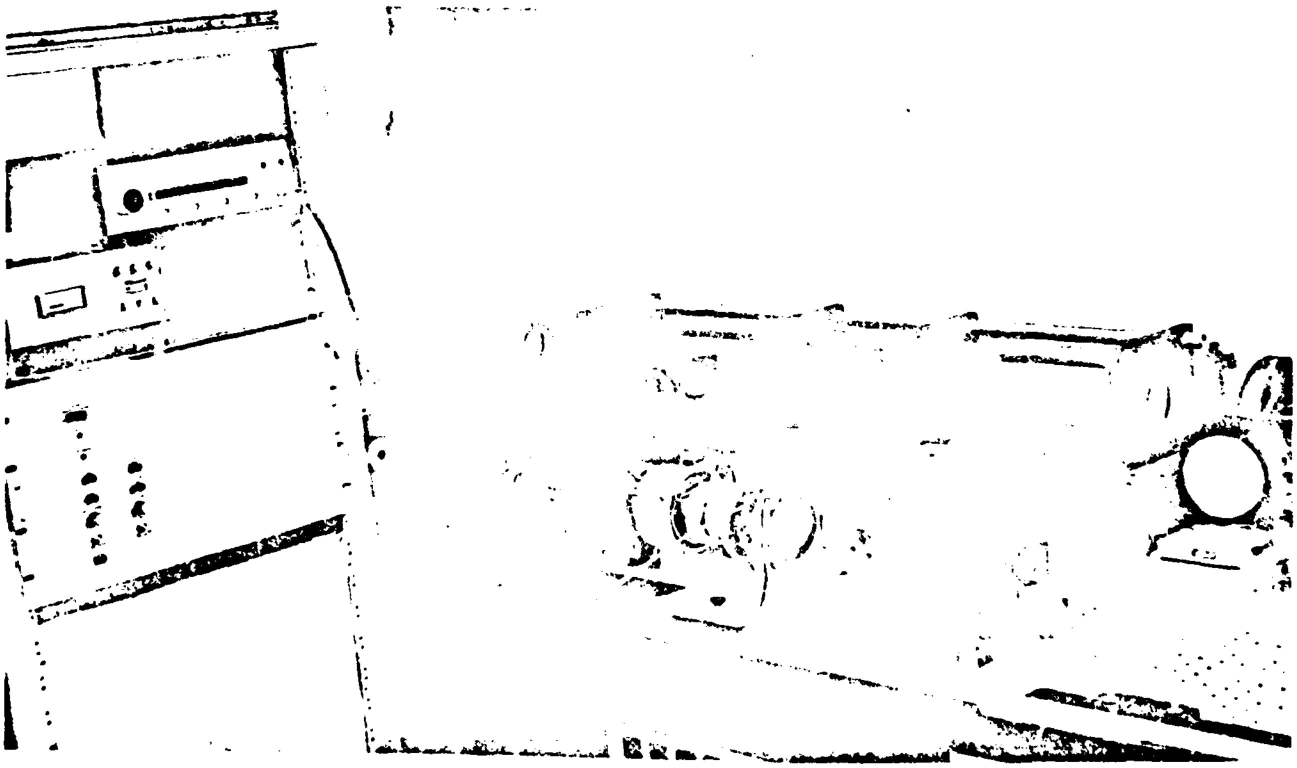


Figure 1b. Photograph of several components of the microcomputer-controlled video system, with the CRT and Liquid Crystal Light Valve in the foreground and the Coherent Optical Processor in the background.

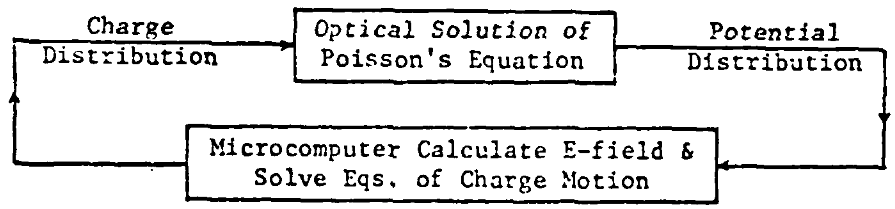


Figure 2. A hybrid iterative processing example for studying plasma stability.

Computing Speed Comparison

1. Solving Poisson's Equation (1000 × 1000 point charges)

A. Optical Solution		
10 Round Trips in Optical Feedback System	100 nsec	
2 Video Frames	70 msec	~1785 times
B. Digital Solution on Fast Digital Computer (which take 1 μsec to perform a floating point multiplication followed by an addition)	125 sec	

2. One Iteration

A. Hybrid Solution Optical Solution of Poisson's Equation Digital Calculation of E-field & Equations of Charge Motion (by microcomputer which takes 120 μsec to perform a floating point multiplication followed by an addition	1.2 sec	~ 100 times
B. Digital Solution	125 sec	

Figure 3. Computing speed comparison between hybrid iterative processing and digital processing.

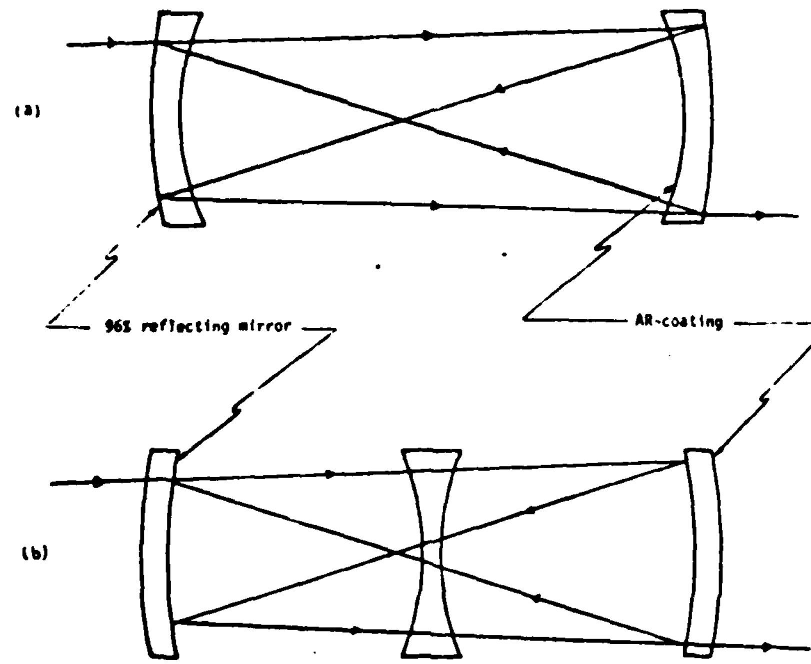


Figure 4. Possible improved designs of the confocal feedback system for increased space-bandwidth product. (a) Negative lenses incorporated into the spherical mirrors by making the radius of curvature of the inner surfaces smaller than that of the outer surfaces. (b) Placing a negative lens in the center of the cavity. This can be done by replacing the optical flats of the liquid gate with planar-concave lenses.

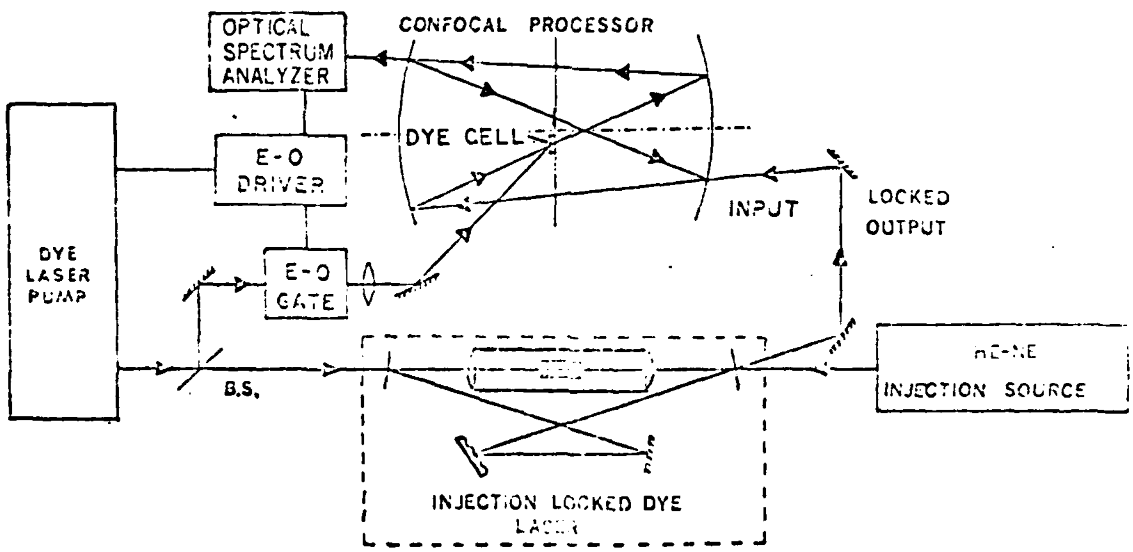
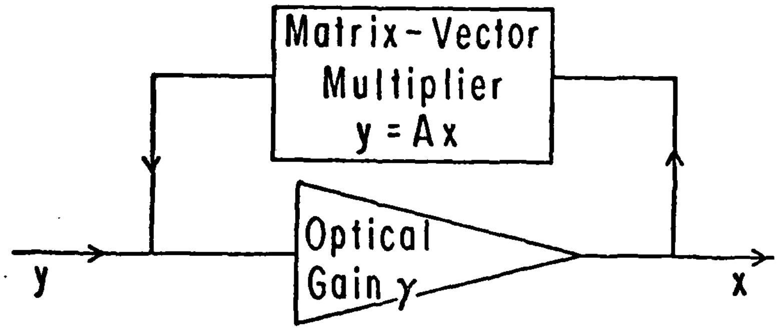


Figure 5. Injection-locked folded cavity ring dye laser and (dye gain) cell for coherent image amplification.

(a) (b) (c)

Figure 6. Spectrum analyzer outputs showing (a) one-ring pattern when the HeNe laser is operated at single axial mode and the dye cell unpumped, (b) two-ring pattern when the HeNe is operated at two adjacent axial modes and the dye cell unpumped, and (c) the locking of the dye amplifier to a single HeNe mode when the dye cell is pumped.

Matrix Inversion



y = ($n \times 1$) column vector

x = ($1 \times n$) row vector

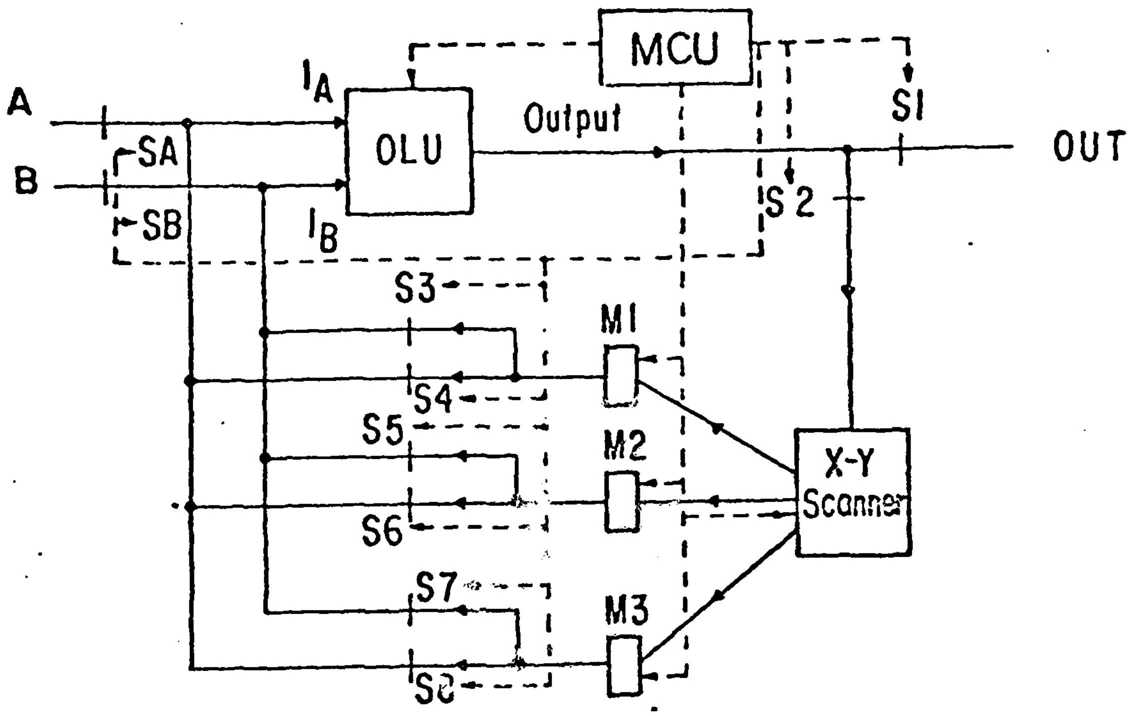
A = ($n \times n$) matrix

$$y - Ax = \frac{1}{\gamma} x$$

$Ax \simeq y$ when γ is large

$$x = A^{-1} y$$

Figure 7. The schematic of an optical feedback system for computing matrix inversion. It contains an optical gain element in the forward path and an optical matrix-vector multiplication system in the feedback path.



----- ELECTRONIC CONTROL SIGNALS, —— OPTICAL DATA SIGNALS

Figure 8. The schematic diagram of a digital optical processor. OLU = optical logic unit, MCU = microprocessor control unit, S = shutters, M - optical memory devices.

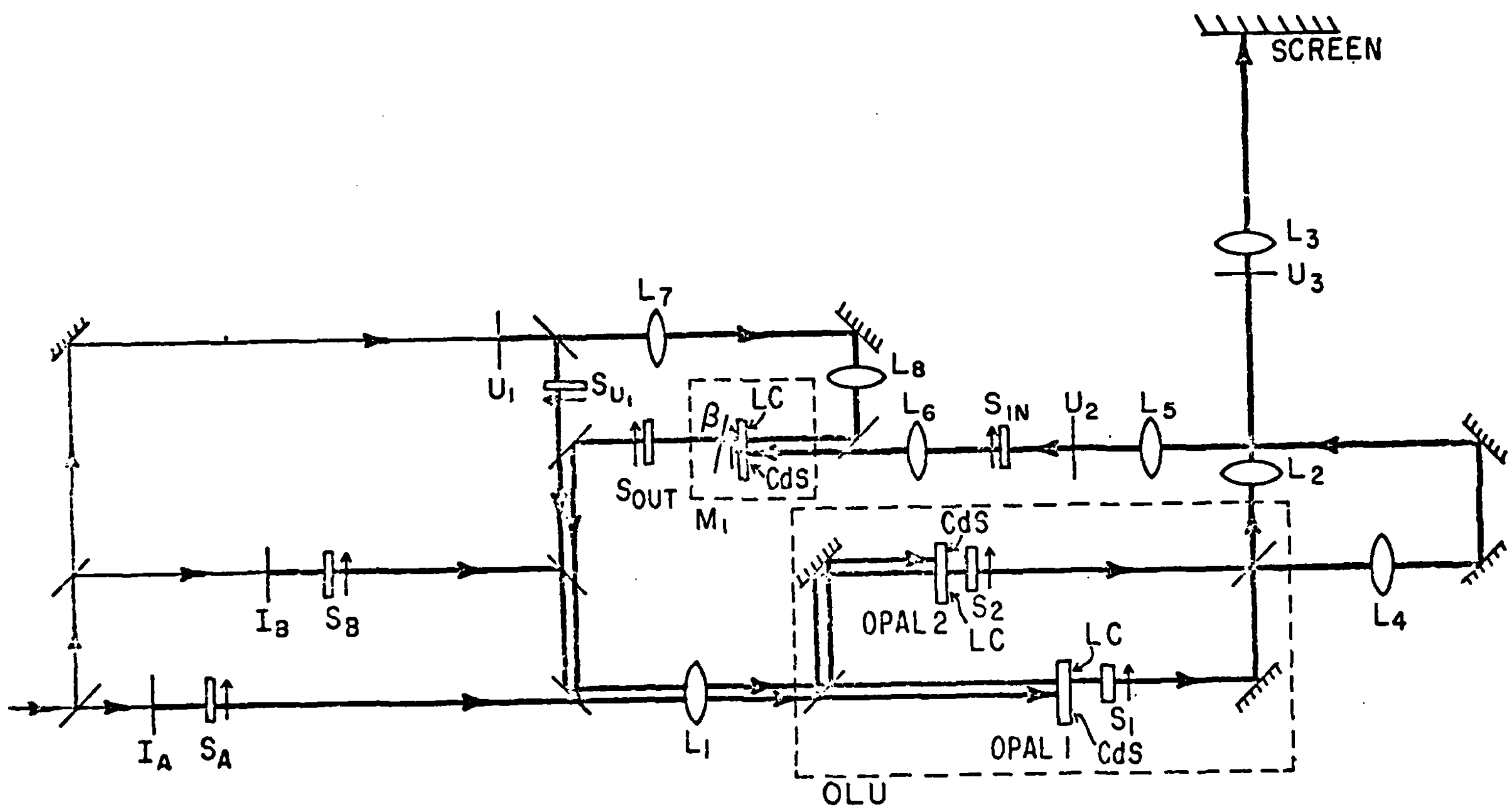


Figure 9. Digital optical processor with single memory (M_1). OLU = optical logic unit, S = shutter, P = polarizer (arrow head behind shutter), and U = mask of unity transmission at all pixels.

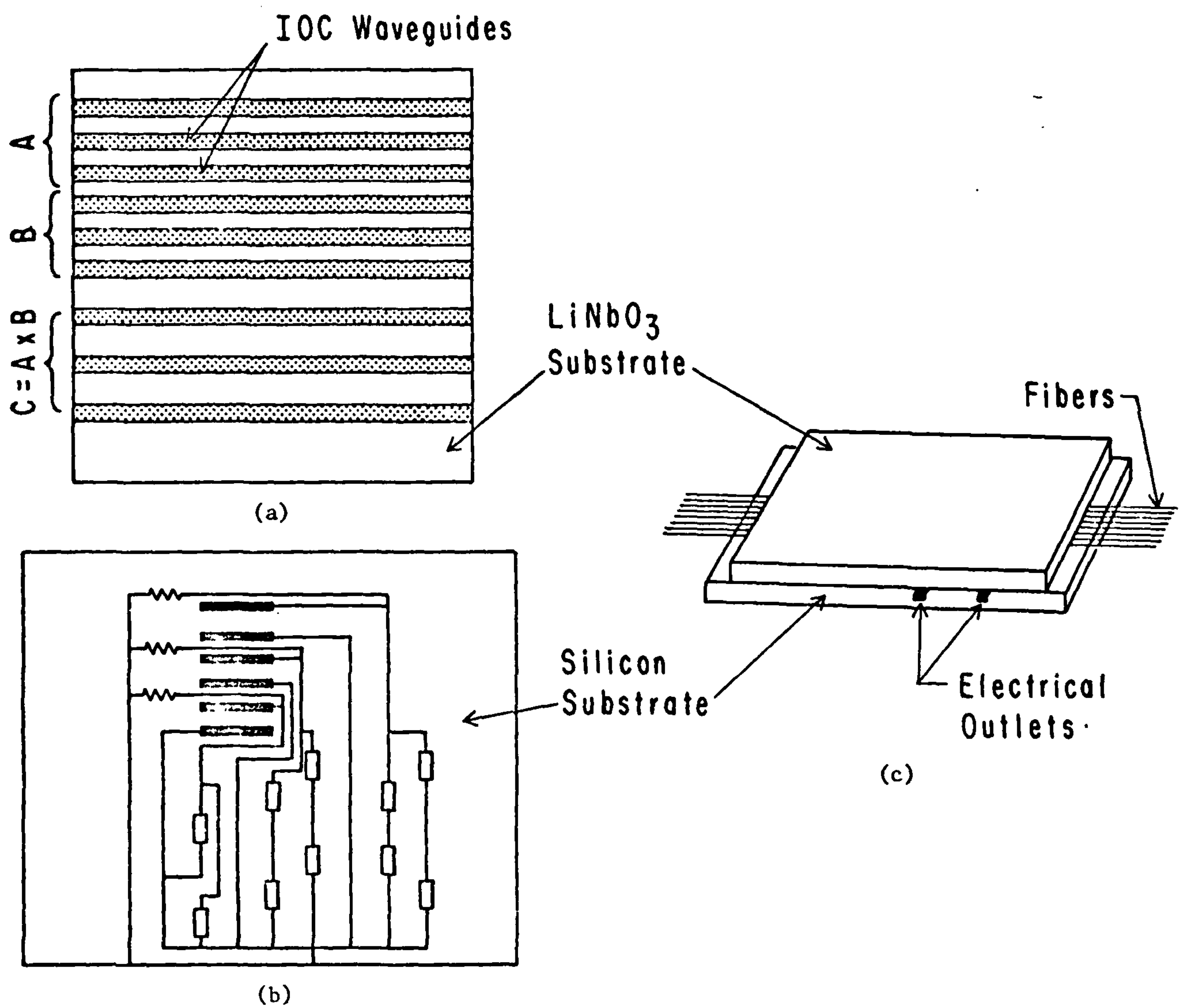
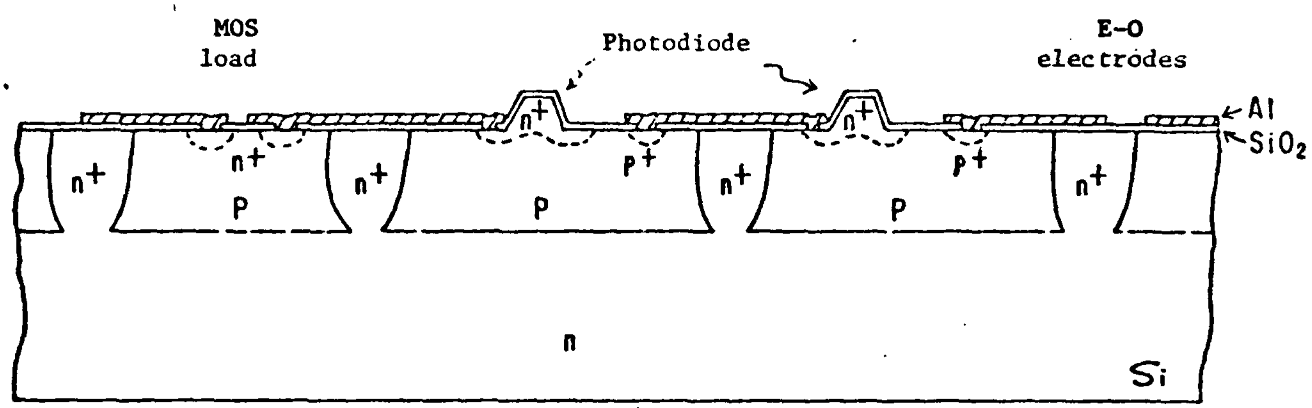
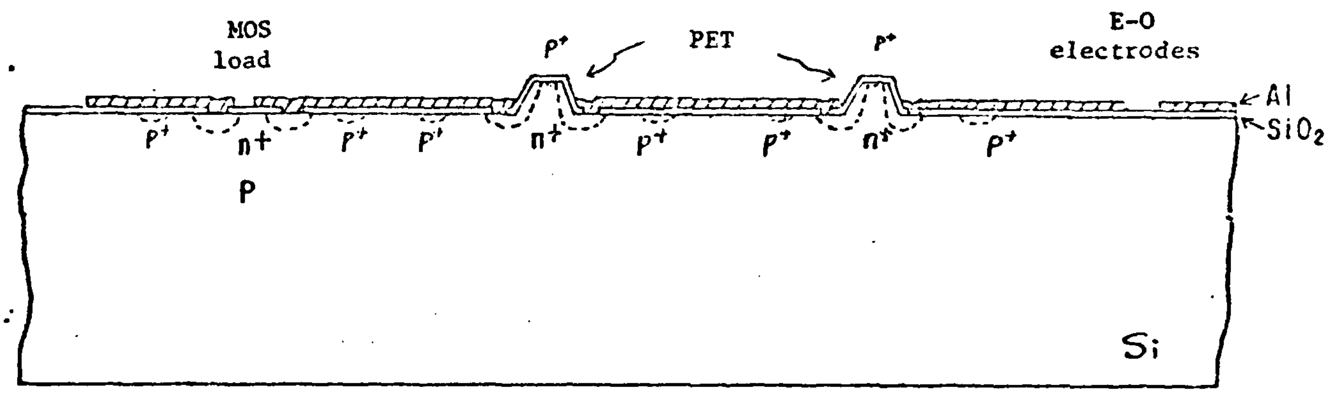


Figure 10. Flip-chip method of binding, which allows interfacing pre-fabricated optical circuits (a) with electrical circuits (b) to produce hybrid circuits (c).



(a)



(b)

Figure 11. (a) n^+p photodiodes, (b) $n^+/p/n^+$ photo-effect-transistor (PET).

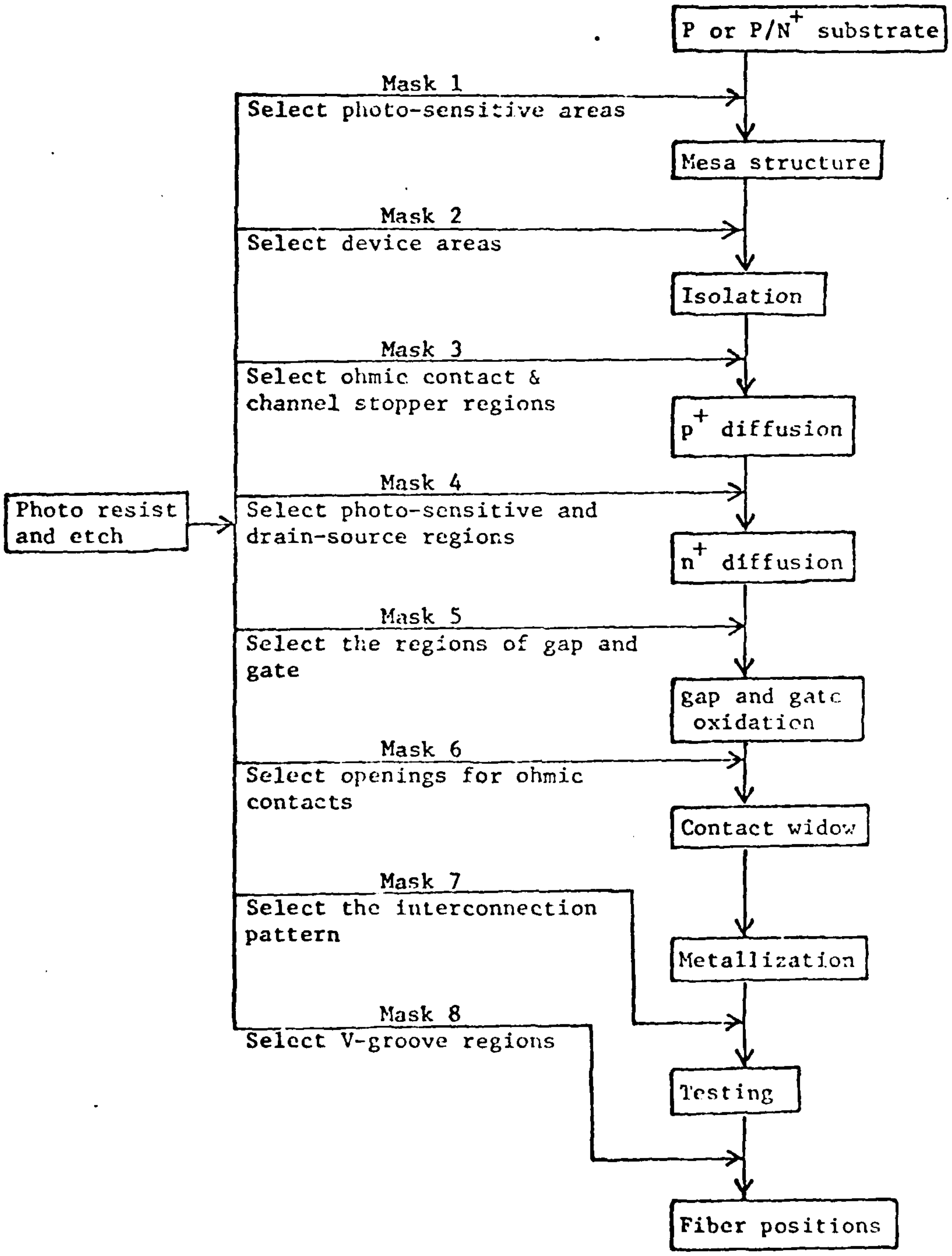


Figure 12(a). Fabricating the IC on Si wafer.

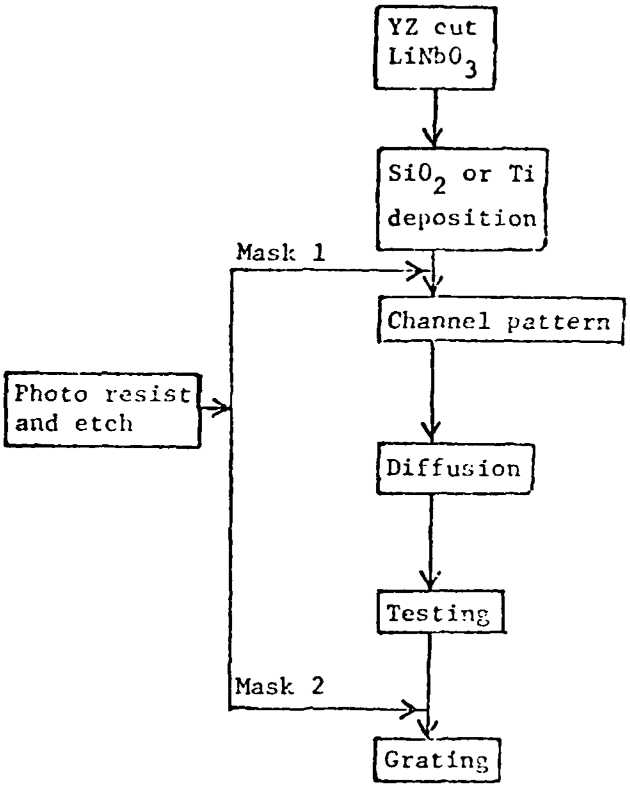


Figure 12(b). Fabricating the IOC on $LiNbO_3$ substrate.

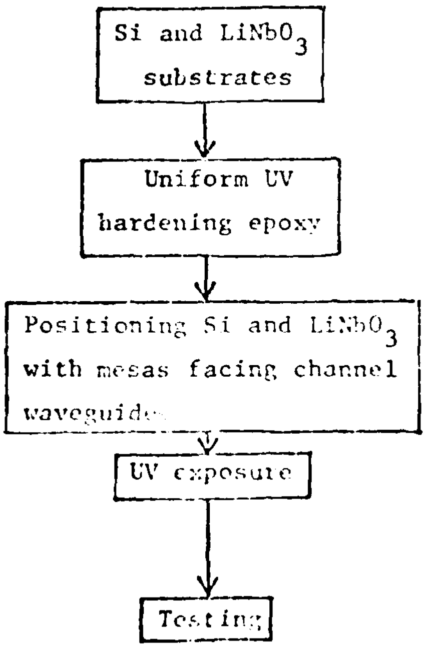


Figure 12(c). Binding Si and $LiNbO_3$ substrates.

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